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The state-of-the-art review on energy harvesting of flow-induced vibrations

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Abstract

In this paper, the current popular flow-induced vibrations energy harvesting technologies are reviewed, including numerical and experimental endeavors, and some existing or proposed energy capture concepts and devices are discussed. The energy harvesting mechanism and current research progress of four types of flow-induced vibrations, such as vortex-induced vibrations, galloping, flutter and buffetting, are introduced. To enhance the performance of the harvesters and broaden the operating range, the researchers have proposed various mechanical designs, methods of the structures’ surfaces optimization and incorporated magnets for multistability. The paper summarizes the works led to current wind energy and hydro energy harvesters based on the principle of flow-induced vibrations, including bladeless generator Vortex Bladeless, University of Michigan vortex-induced vibrations aquatic clean energy (VIVACE), Australian BPS company’s airfoil tidal energy capture device bioSTREAM, and others showing the gradual progress and maturity of the flow-induced vibrations energy harvesters. The article concludes with a discussion on the current problems in the area of flow-induced vibration energy capture and the challenges the area faces.

Keywords: Flow-induced vibration; Energy harvester; Hydrokinetic energy; Wind energy

Introduction

In recent years, the burning of oil, coal and other fossil fuels has caused increasingly serious environmental problems, and fossil energy is increasingly exhausted, thus the issue of harvesting clean and renewable energy from the environment remains a critical research hotspot [1-3]. A flow-induced vibrations (FIVs) energy harvester is a micro-environmental energy-capturing device designed based on the principle of flow-induced vibrations. The device can harvest energy from the surrounding flow field to supply energy to a micro-electro-mechanical system (MEMS) and wireless sensing system to achieve continuous monitoring of the system [4].

FIVs is a very common physical phenomenon in engineering field that is caused by
aerodynamic instability or vortex shedding when fluid passes around a slender structure [5]. Although FIVs may cause structural damage and huge economic losses, it also has great potential for utilization, which can be used to harvest the hydraulic energy, wind energy, and energy of flowing gas in HVAC. For example, the VIVACE proposed by Bernitsas and Raghavan et al. [6], university of Michigan, converts tidal energy into vibration energy by using the principle of vortex-induced vibrations (VIVs), and then converts vibration energy into electrical energy through electromagnetic induction device for harvesting. Compared with traditional hydraulic generators, VIVACE has long service life, low maintenance cost and high energy density. Vortex bladeless, a bladeless wind turbine developed by a Spanish company [7], uses the principle of VIVs to harvest wind energy. The device has the advantages of simple structure and low cost. In recent years, a large number of new FIVs energy harvester have been proposed, so it is necessary to review the current FIVs energy harvesting technologies and devices, which is helpful for researchers to understand the latest research progress.

FIVs energy harvest involves three-field coupling of a flow, structure and electricity, and this coupling is complex. In this paper, the basic mechanism of energy harvesting of vortex-induced vibrations, galloping, flutter and buffeting as well as the relative research directions at present are summarized firstly. Then, the common wind and hydro energy harvest devices by flow-induced vibrations are introduces and possible issues are discussed. Finally, the challenges of FIVs energy harvesting are debated.

1 Current Research Status of Flow-induced Vibration Energy Harvesting

According to the different vibration mechanisms, the FIVs for energy harvesting can be divided into four categories: VIVs, galloping, flutter and buffeting, as shown in Fig. 1. The VIVs and buffeting belong to a family of forced response vibration. The FIVs energy harvesters designed based on response vibration can operate normally at low flow velocities, but the working bandwidth is limited by the natural frequency of the structure, and they are mostly used for the low-speed flow energy harvesting. The galloping and flutter belong to a family of limit-cycle vibration. Compared with the previous family, the cut-in speed of in this group is higher, but its effective operating speed range is wider, and larger response amplitude under higher wind speed can be observed, which is beneficial for energy harvesting. This section discusses these four kinds of common FIVs energy trapping devices.

![Figure 1. Classification of Flow-induced vibrations [8].](image-url)
1.1 Vortex-induced vibrations

VIVs are closely related to a flow field velocity and bluff body structures [9]. When fluid flows around the bluff body, the vortex occurs periodically in the wake behind the bluff body. The shedding frequency \( f \) of the vortex is defined as \( f = uSt/L \), where the Strouhal number \( St \) is regarded as a constant within a certain Reynolds number range (when \( 300 < Re < 1.5 \times 10^5 \), \( St = 0.2 \) ) [10], \( u \) is the incoming flow velocity and \( L \) is the characteristic length. The vortex shed behind the bluff body will generate an asymmetric pressure field around it, then the bluff body will be subjected to alternating aerodynamic forces, resulting in a finite amplitude of vibrations. With the change of the incoming velocity, the frequency of vortex shedding varies. When the vortex shedding frequency is close to the natural frequency of the bluff body, resonance will occur and the bluff body will undergo a high amplitude vibration. At the same time, the phenomenon of frequency lock-in may occur implying that within a certain range of the incoming flow velocities, and the frequency of vortex shedding will no longer change with the flow velocity. Facchinetti et al. [11] pointed out that the structural oscillations equation and the wake oscillator model coupling can be used to describe the vortex-induced vibrations. For a simple single-degree-of-freedom (SDOF) piezoelectric energy capture model represented by a cantilever beam, an electromechanical coupling term can be introduced on the basis of the vortex-induced vibrations model of Facchinetti et al. [11]

\[
\ddot{\eta} + \left[ 2\zeta \omega + \left( \frac{1}{2} C_l \rho_0 D U_0 L_0 \left( \phi(L_b) + \frac{D}{2} \varphi'(L_b) \right) \right) \right] \dot{\eta} + \omega^2 \eta + \theta V = \frac{1}{4} C_l \rho_0 D U_0^2 L_0 \left( \phi(L_b) + \frac{D}{2} \varphi'(L_b) \right) q
\]

\[
\ddot{q} + \lambda \omega_{shed} \left[ q^2 - 1 \right] \dot{q} + \omega_{shed}^2 q = \frac{A}{D} \left[ \phi(L_b) + \frac{D}{2} \varphi'(L_b) \right] \dot{\eta}
\]

\[
\frac{V}{R_L} + C_p \dot{V} - \theta \dot{\eta} = 0
\]

In the above equations, (1) is the structural oscillations equation, Eq.(2) is the wake oscillator equation, and (3) represents the circuit equation. Here \( \eta \), \( \dot{\eta} \) and \( \ddot{\eta} \) represent the displacement, velocity, and acceleration of the oscillator respectively, \( \zeta \) represents a damping coefficient, \( \omega \) is the natural frequency of the structure, \( \omega_{shed} \) is the vortex shedding frequency, \( \rho_0 \) and \( U_0 \) represent the density and flow rate of the incoming stream respectively, \( \phi(L_b) \) is the end displacement of the cantilever beam. \( C_l \) and \( \rho_0 \) represent the drag and lift coefficients respectively, \( q \) represents wake displacement. \( V, R_L, C_p \) and \( \theta \) are the circuit parameters.

The efficiency of the vortex-induced vibrations energy capture device is higher when it works within the lock-in frequency region. When the incoming flow velocity exceeds the corresponding velocity range, the vibrations will be out of tune, their amplitude decreases sharply, as well as the efficiency of energy capture. Therefore,
the broadening the width of the lock-in frequency region becomes the focus of some studies on the energy capture of VIVs. A classical structure of vortex-induced vibrations energy capture device is based on a cylindrical bluff body, and researchers have conducted a lot of work on the improvement of the structure. Azadeh-Ranjba et al. [12] studied the influence of the aspect ratio of a rigid cylinder on VIVs, and the results suggested that the increase of the length-width ratio of the finite length cylinder can not only increase the response amplitude of the rigid cylinder, but also broaden the lock-in frequency region of the VIVs. Alireza et al. [13] studied an effect of a spring stiffness of a water energy capture device on VIVs under high Reynolds numbers ($1.5 \times 10^4 \leq Re \leq 6 \times 10^4$). In the experiment, five springs of different stiffness were selected within the range of 125 N/m $< K < 495$ N/m, and the system responses under different stiffness were studied by changing the natural frequency of the system. The experimental results suggested that the maximum amplitude and the lock-in frequency region of the system are closely related to the spring stiffness, and the increase of the natural frequency will result in the increase of the response amplitude and widening the frequency range of the system. In addition, Wang et al. [14] proposed a new S-E VIVPEH (Scanlan-Ehsan vortex induced vibrations piezoelectric energy harvester) lumped parameter model. In that work, the authors argued that the traditional semi-empirical mode (such as wake oscillator model, structural vibration model, etc.) is not suitable for predicting the performance of the vortex-induced vibrations energy harvester with a non-circular cross-section structure. The S-E VIVPEH model use a decay to resonance experiment to identify the semi empirical parameters. Compared with other semi-empirical models, the advantage of the model is that there is no restriction on the cross-section structure of the bluff body in the VIV calculation. In addition, the wake vortex distribution also has a great impact on the VIV energy conversion efficiency [15-19]. Zhang et al. [15] proposed adding a fixed cylindrical bluff body to the piezoelectric energy harvester of a cantilever beam structure, as shown in Fig. 2. The cylinder is located in the wake region of the original cylinder, and distance $L$ between the two cylinders can be adjusted. The experimental results are shown in Fig. 3. It can be seen that the bandwidth of the structure lock-in frequency region is wider than that of the original device, and the bandwidth decreases as the distance $L$ increases. Song et al. [16] studied the performance of adding a splitter plate at the end of a cylindrical vibrator for the vortex-induced vibration energy harvester. The experimental device is presented in Fig. 4. The experimental data shows that when the splitter plate exists, the working bandwidth of the harvester increases gradually and the peak voltage decreases with the increase of the normalized length $L_{SP}/D$ of the plate. When $L_{SP}/D$ is close to 0.5, the VIVs will converge to a galloping motion, and thereafter the peak voltage increases as the wind speed increases. When $L_{SP}/D$ is close to 1.0, the voltage curve will show a downward branch, mainly due to the shear layer separation.
Figure 2. The schematic of the improved energy harvester [15].

Figure 3. Performance of the energy harvester with the interference cylinder as a function of the wind speed for different values of the spacing distance [15].

Figure 4. Wind energy harvester with splitter plates on the circular in the wind tunnel [16].

In order to improve the efficiency of wind energy harvesting, Wang et al. [4] investigated the influence of the Passive Turbulence Control (PTC) devices on the VIVs energy harvester. In order to determine the optimal PTC structure in the experiment, Wang et al. compared the energy harvester with different numbers and
sizes of PTC structure, as shown in Fig. 5. Fig. 6 shows the experimental results. It should be noted that the PTC structure has a great influence on the working bandwidth and output voltage of the energy harvester. Reasonable adjustment of the rough belts structure can improve the performance of the vortex-induced vibration energy harvester. VIVs also occur in bluff bodies of non-circular cross-section under certain conditions [20-24]. Compared to the flow around the cylinder, when the fluid passes the non-circular cross-section bluff body, the detached vortices are asymmetrically distributed. The separation of the boundary layer of the square column structure is different from that of a circular cylinder. Usually, the boundary layer separation occurs at the leading edge angle, and the separation point is not changed with the Reynolds number. Therefore, the influence of the attack angle is the focus of some researches on the square-column vortex-induced vibrational energy harvesting [20]. In addition, due to the aerodynamic instability of the square-column structure, the galloping can occur at higher wind speeds. Compared with the single-mode VIVs, the vortex-vibration-acceleration mode can significantly improve the working efficiency [21].

Figure 5. Experimental circular cylinder cross-section with different PTC structure [4].

Figure 6. Comparisons of energy harvesting efficiency between PTC cylinders with smooth cylinder: bandwidth of lock-in and the peak value of voltage output [4].

The current research on vortex-induced vibration energy harvesting can be divided into the following streams: (1) vortex-induced vibration piezoelectric energy harvesting with a nonlinear magnetic force [25-29]. The structure of a piezoelectric energy capture device can be improved by introducing a magnetic field, and the
natural frequency of the structure can be reduced as well. By adjusting the natural frequency of the structure, the device is capable of operating at low wind speeds. For example, Zhang et al. [27] proposed to add a pair of mutually exclusive magnets to the piezoelectric energy capture device of the cantilever beam structure, one is placed at the bottom of the bluff body, and the other is placed at the bottom of the support, as shown in Fig. 7. The experimental results suggest that the energy capture efficiency of the device is improved by 29% and the lock-in frequency range is widened by 138% when the nonlinear magnetic field force is applied, which obviously demonstrates the positive effect. (2) Hybrid energy harvester based on VIVs [30-34]. The energy harvesting efficiency of the device can be improved by using a combination of electromagnetic, piezoelectric, electrostatic, and dielectric energy transduction mechanisms. The structure of piezoelectric electromagnetic hybrid energy harvester proposed by Zhao et al. [31] is shown in Fig. 8. The electromagnetic induction element is added to the cantilever piezoelectric device creating a combination of vibrational piezoelectric and electromagnetic power generation. The maximum output power of this device can reach 16.55mW in the experiment tests, and the observed power generation efficiency is higher than the single mode piezoelectric and electromagnetic energy capture devices under the same operating conditions. (3) Vortex-induced vibration energy capture device with a multi-degree-of-freedom (MDOF) structure [35-40]. Compared with SDOF oscillators, the motion of MDOF oscillators is more complex, but its practical application prospect is broader. Guilherme et al. [35] constructed a two-degree-of-freedom (TDOF) vortex-induced vibration piezoelectric energy harvesting model as shown in Fig. 9, where the rigid cylindrical oscillator moves in both the cross-wise and in-line directions. The authors established the electromechanical coupling equation for this model, and studied the impact of the in-line to cross-wise natural frequencies ratio $f^*$ and the parameter $\sigma_1$ ($\sigma_1$ is the correlation dimensionless quantity of the electromechanical coupling coefficient of the system) on the system response and energy harvesting efficiency. Subsequently, Guilherme and Lucas et al. [36] studied the influence of degrees of freedom on the energy harvesting efficiency of the vortex-induced vibrations capture energy device. The results suggest that the energy harvesting efficiency of the TDOF system is significantly higher than that of the SDOF system under various wind speeds due to the much higher amplitude of the cross-wise oscillations of the TDOF.
Figure 7. The Schematic of piezoelectric energy capture device with a pair of mutually exclusive magnets [27].

Figure 8. Schematic of the energy harvester [31].

Figure 9. Schematic representation [35].

1.2 Galloping

Galloping is a typical phenomenon of self-excited vibrations caused by aeroelastic instability, which occurs mostly in long and flexible structures with edges and corners. It usually appears to be related to the velocity of the incoming flow and the relative
orientation of the fluid with respect to the structure, and is usually characterized by
low-frequency and high-amplitude oscillations [9]. The galloping energy is mostly
based on the principle of galloping, and the typical SDOF model of the galloping
energy harvester is shown in Fig. 10, while the governing equation of the model can
be written as\[41\]

\[
M\ddot{w}(t) + C\dot{w}(t) + K w(t) + \theta V(t) = F_Z(t)
\]

\[
V(t)/R_i + C^s V(t) - \theta \dot{w}(t) = 0
\]

where \( M, C, K \) are structural parameters related to the system, \( M \) is the mass of the
square cylinder, \( C \) is the damping of the system, \( K \) is the spring stiffness, \( w(t) \) is the
lateral displacement of the end of the bluff body, \( F_Z(t) \) is the aerodynamic force of the
bluff body applied in the flow field. Tabesh et al. [42] transformed the circuit
parameters into mechanical parameters by performing a Laplace transform on Eq.(4),
using electrical damping \( C_e \) and electrical stiffness \( K_e \) to represent the effect of the
load circuit on the system, and decoupling the equation:

\[
M\ddot{w}(t) + (C + C_e)\dot{w}(t) + (K + K_e)w(t) = F_Z(t)
\]

(5)

where the electrical damping and electrical stiffness are expressed as

\[
K_e = \frac{(R_i\omega\theta)^2 C_s^5}{1 + (R_iC_s^5\omega)^2}, \quad C_e = \frac{R_i\theta^2}{1 + (R_iC_s^5\omega)^2}
\]

Barrero-Gil and Abdelkefi et al. [43, 44] pointed out that, the time scale of the
structural oscillations characteristics of the galloping \( 2\pi/\omega \) is much larger than the
characteristic time scale of the fluid passing the cylinder \( D/U \), so the quasi-static
theory can be used to obtain the aerodynamic force \( F_Z(t) \). By using a polynomial
fitting approximation method, \( F_Z(t) \) can be expressed as a cubic polynomial expansion
of the angle of attack \( \alpha \), where the polynomial coefficients are independent of the
Reynolds number, so

\[
F_Z(t) = \frac{1}{2} \rho_s U S A_1 \alpha + \frac{1}{2} \rho_s U^2 A_3 \alpha^3
\]

(7)

Here \( \rho_s \) is the density of the incoming flow, \( U \) is the velocity of the incoming flow, \( S \)
represents the cross-sectional area of the square column in the vertical flow direction,
\( A_1 \) and \( A_3 \) are empirical coefficients related to the shape of the oscillator, the angle of
attack \( \alpha \) can be written as \( \alpha = \dot{\omega}(t)/U \) (the rotation of the square column was
ignored).

\[
M\ddot{w}(t) + \left( C + \frac{R_i\theta^2}{1 + (R_iC_s^5\omega)^2} \right) - \frac{1}{2} \rho_s U A_1 \left( \frac{\dot{w}(t)}{U} \right)^2 + \left( K + \frac{(R_i\omega\theta)^2 C_s^5}{1 + (R_iC_s^5\omega)^2} \right)w(t) = 0
\]

(8)
One can regard the aerodynamic force on the square column as a nonlinear damping element, so the damping term in the galloping mathematical model can be expressed as the sum of a linear damping and a nonlinear damping, thus the damping coefficient form is \[ [45]\]

\[
C + \frac{R_1 \theta^2}{1 + (R_1 C^2 \omega)^2} - \frac{1}{2} \rho_o S U A_i \left( \frac{\dot{w}(t)}{U} \right)^2 \]

(9)

For the galloping energy harvester, the linear damping term determines the threshold wind speed. By reasonably adjusting the structural parameters of the device and the shape structure of the oscillator, energy harvesting can be achieved at a relatively small wind speed. At the same time, the output energy efficiency increases with the increase of the wind speed. The nonlinear damping term has a great influence on the maximum amplitude of the harvester and provides a vibration mitigation effect ensuring stable oscillations of the system.

![Figure 10. Schematic of a bluff body subjected to galloping.](image)

In the studies of the galloping energy harvesting, the applied aerodynamic force \[F_{Z(t)}\] of the bluff body is not only related to the structural parameters of the harvester and the incoming wind speed, but also affected by the surface condition of the bluff body. For the galloping energy harvester with relatively complicated structure, it is always difficult to determine the aerodynamic forces. Javed et al. [46] used a distributed parameters model to study the effects of different aerodynamic load representations on the galloping harvesting. In the experiment, the polynomials approximation of the aerodynamic force with different coefficients were used to calculate the efficiency of the galloping energy harvesting under the same working conditions. The results show that the maximum displacement and energy harvesting efficiency of the harvester may change when different aerodynamic polynomials are used. In order to study the influence of the wall on the aerodynamic forces, Soohwan et al. [47] constructed a model of a galloping-based piezoelectric wind energy harvester with a peripheral structure, and the structure of the harvester is shown in Fig. 11. Then, a new quasi-static aerodynamic model with two variables, the angle of attack \(\alpha\), the nearest wall distance \(d_y\) was proposed, and the theoretical model of the energy harvester was established based on the Euler–Bernoulli beam theory and linear
piezoelectricity. The experimental results show that the model can predict the limit cycle oscillations of the bluff body well, and the accuracy ($R^2 > 0.99$) is higher than the model accuracy without considering the wall surface ($R^2 > 0.90$). On the other hand, the load circuit has a great influence on the galloping energy harvester [48-54].

Tan et al. [48] first studied the effect of a load circuit with inductance on the efficiency of the cantilever beam piezoelectric energy harvester. The result shows that the maximum power output under the optimal resistance can be achieved by connecting the inductor and the resistor in series or in parallel. At the same time, the introduction of the inductance component in the load circuit can increase the maximum output power at a high wind speed, reduce the displacement of the bluff body, and improve the stability of the system. Then, the effects of the DC and AC circuit interfaces on the efficiency of the energy harvester were explored [50]. It was found that when the wind speed is small, the minimum threshold wind speed, the maximum tip displacement of the bluff body and the maximum output power of two kinds of energy harvesters are almost the same, but the harvester with the DC circuit interface has smaller maximal electrical damping with larger optimal load resistance. When the wind speed is high, the harvester with AC circuit interface can obtain higher output power. Zhao et al. [52] compared the effects of the four common load circuit interfaces (synchronous charge extraction circuit, series and parallel synchronous switch inductor circuits, standard circuits) on the galloping energy harvesting. They found that the synchronous charge extraction circuit is suitable for weak coupling and higher wind speed conditions, and synchronous switch inductor circuits are suitable for weak and moderate coupling as well as lower wind speed conditions. For high terminal loads, a series synchronous switch inductor circuit should be used; for small terminal loads, a parallel synchronous switch inductor circuit should be used. Under the condition of strong coupling, the harvester with synchronous switch inductor circuit and the standard circuit have the same output power, and a standard circuit with a simpler structure is generally selected. In addition, Barrero-Gil et al. [55] investigated the improvement of galloping energy harvester by actively rotating the galloping bluff body. The experimental results showed that imposing externally a rotation of the body proportional to the angle of attack could improve the energy harvesting efficiency of the energy harvester, which provide a reference for improving the galloping energy harvester. 

![Diagram of galloping energy harvester](image)
The current research on the galloping energy harvesting can be divided into the following streams: (1) The galloping-based energy harvester with nonlinear magnetic forces [56-60]. Bibo et al. [56] compared the output voltage and output power of galloping energy harvesters with different types of nonlinear forces (softening, hardening, bi-stable) for different wind speeds, and the results showed that the nonlinear forces had a great impact on the performance of galloping energy harvesters. Yang et al. [59] investigated the performance of a double-beam piezo-magneto-elastic wind energy harvester (DBPME-WEH) for different wind speeds. Compared with the double-beam piezoelectric wind energy harvester (DBP-WEH), the critical wind speed of the DBPME-WEH is reduced to 41.9%. (2) The shape and structure optimization of a bluff body. Compared with the traditional prismatic structure, new structures such as T-shaped, Y-shaped, and D-shaped, etc. have higher energy conversion efficiency [61-68]. In addition, the surface structure of the bluff body has also a great influence on the efficiency of galloping energy harvesters. There are number of examples like the whale flipper biomimetic structure proposed by Ewere et al. [69], the passive control of the column with PTC rough belts [70, 71], adding attachment to bluff body surfaces [72-74]. Wang, Zhou et al. [72] proposed a novel galloping-based piezoelectric energy harvester with Y-shaped attachment at the bluff body surface (GPEH-Y), and studied the effect of the attachment on the energy harvester. The schematic diagram of the device is shown in Fig. 12. Firstly, the lattice Boltzmann method (LBM) was used to compare the vibration amplitude and frequency of a smooth cylinder and cylinder with Y-shaped attachment at a varying wind speed. It was found that the vibrations of the cylinder changed from vortex induced vibrations to galloping by adding the attachment, and the results were further verified by the wind tunnel experiments. Then these results were compared with the performance of GPEH-Y, GPEF-Square and VIVPEH under different resistive loads and wind speeds, and they are shown in Fig. 13. Compared to GPEH-Y and GPEF-Square, the minimal threshold wind speed of the VIVPEH was lower and it enters the frequency lock-in region earlier, but the bandwidth of a working wind speed of VIVPEH \( (1 \text{m/s} < U < 1.42 \text{m/s}) \) is much smaller than that of GPEH-Y \( (U < 1.28 \text{m/s}) \). In the operating range of a wind speed \( U \leq 2 \text{m/s} \), GPEH-Y increases the maximum output voltage by nearly 300% compared with VIVPEH, and the maximum output power increases by nearly 400%. In addition, Ding et al. [74] compared the performance of energy harvester with symmetrical fin-shaped rods (FSR) at different placement angles, and the experimental results showed that the optimal placement angle of FSR was 30º-60º. (3) Hybrid galloping energy harvesting. Compared with the single-mode energy harvester, the harvester using galloping and vortex-induced vibrations coupling [21, 22, 75], galloping and base-vibration coupling [76-79] can improve energy harvesting efficiency and widen the bandwidth of the harvester. Zhao et al. [79] proposed a hybrid energy harvesting device as shown in Fig. 14, which introduces a high frequency mechanical stopper as a supplemental energy source to improve the performance of the device. The experimental results show that the working bandwidth and the energy harvesting efficiency of the hybrid device are
greatly improved compared with the original energy harvester. The bandwidth is increased by nearly 8.5 times, and the efficiency of energy harvesting has increased nearly twice under the wind speed of 5 m/s and the base vibration acceleration of 1 m/s².

Figure 12. Schematic diagram of the GPEH-Y: (a) Equivalent schematic diagram; (b) physical diagram in the wind tunnel test [72].

Figure 13. Experimental comparison of the GPEH-Y, the VIVPEH, and the GPEH-Square with different load resistances: (a) Output voltage; (b) output power [72].

Figure 14. The enhanced broadband wind and base vibration EH system [79].

1.3 Flutter

Flutter is a typical two-dimensional aeroelastic instability phenomenon involving
bend and twist vibrations, which occur mostly in the high-speed flow field [80]. Flutter can result in structural damages of the aircraft wings and tail in aerospace structures [81]. Due to the existence of a phase difference between the instantaneous aerodynamic force acting on the structure and the structural displacements where the flutter appears, positive feedback can occur during the vibrations of the structure and the aerodynamic force. As the structure constantly absorbs energy from the flow, the amplitude of vibrations will increase continuously and diverge if the aerodynamic damping is greater than the mechanical damping [9]. In terms of the energy harvesting phenomenon, the flutter-based energy harvester have a great potential for development because of self-excitation, divergence, and large amplitudes of vibrations caused by flutter.

Santos et al. [82] studied the response of the harvester at high subsonic conditions using a typical flutter energy harvesting model with a pitching structure, as shown in Fig. 15. They found that the stiffness of the structure has a little influence on the structural response, and the position of the elastic axis and the inertia parameters have a great influence on the response. Ardito and Musci [83] studied the application of the flutter energy harvesting in MEMS. In the study, they first discussed the modeling method of the cantilever beam structure piezoelectric flutter energy harvester, then studied the aerodynamic effect of the Reynolds number on the device, and verified the feasibility of flutter energy harvesting. By analyzing the experimental results of Bruno and Fransos [84], it is found that the mechanism of a cantilever beam flutter instability may change with Reynolds number. In addition, they studied the effects of RC load circuit and RLC load circuit on the device's energy harvesting efficiency. The experimental results show that the RLC load circuit has higher efficiency than the RC pure-resistance circuit. Rong et al. [85] performed a stability analysis on a flutter energy harvester, which consisted of a thin plate and a flap hinged at its end, and obtained the effect of a sheet size on the threshold wind speed. The results show that when the aspect ratio of the thin plate increases, the minimal threshold wind speed decreases, and the width of the flap has also a great influence on the threshold wind speed. Tang et al. [86] studied the efficiency of a flutter energy harvester consisting of a piezoelectric plate and a load circuit, which harvesting energy in different directions of an incoming flow. The results provide a reference for the improvement of the flag-type energy harvesting device. Pigolotti et al. [87] conducted out the wind tunnel experiments and numerical linear analysis on the two-degree-of-freedom flutter model to study its responses under the critical and supercritical conditions, as shown in Fig. 16. By optimizing the load circuit and structure of the energy harvester, the performance of the harvester can be improved [88-94]. Grainger et al. [88] increased the output power of the circuit by tuning resistors. Pasquato et al. [90] proposed that the flutter energy harvester can be equipped with a dynamic adjustment system to track and adjust the harvester to the maximum power output point, thereby improving the stability and application range of the device. Hafezi et al. [91] added a moving slider to the piezoelectric energy harvester with a cantilever beam structure to improve the device performance by moving the slider. The device structure is shown in Fig. 17. The experimental results show that the starting wind speed of the harvester
can be effectively adjusted and the output power can be increased by changing the position of the slider. Chawdhury et al. [94] optimized the T-type cantilever beam structure flutter energy harvester. In the simulation, the parameters such as the length, width, and end height of the cantilever beam were optimized, and the output power of the energy harvester was taken as the objective function. The optimization results show that the output power of the harvester at low wind speed can be improved by reasonably adjusting the parameters of the cantilever beam structure. When the wind speed is 4m/s, the output power of the captive device can reach 0.65mW.

![Diagram of electric-aeroelastic model](image1)

Figure 15. Schematic representation of the electric-aeroelastic model [82].

![Diagram of two-degree-of-freedom flutter problem](image2)

Figure 16. Sketch of the two-degree-of-freedom flutter problem [87].

![Diagram of adaptive aeroelastic piezoelectric harvester setup](image3)

Figure 17. Schematic top view for adaptive aeroelastic piezoelectric harvester setup [91].

1.4 Buffeting

Buffeting is a process of periodic vibration caused by the effects of upflow wakes or natural turbulence, usually occurring in unstable flow fields. The mechanism of buffeting is similar to that of VIVs, the magnitude of the fluid force is independent of
the structure motion, and the resonant frequency is affected by the natural frequency of the structure [95]. Typically the governing equation of a buffeting SDOF system can be expressed as

\[ M\ddot{w} + C_{st}\dot{w} + K w = F_{\text{MIM}}(t) + F_{\text{EIM}}(t) \]  \hspace{1cm} (10)

where \( M \), \( C_{st} \), \( K \) are mechanical parameters associated with the system, \( M \) is mass, \( C_{st} \) is system damping, \( K \) is spring stiffness, and \( F_{\text{MIM}} \) and \( F_{\text{EIM}} \) are unsteady aerodynamic forces of the fluid.

The buffeting energy harvester generally adopts a wake vortex-induced structural vibrations design or a multi-column structure design. Hu et al. [96] constructed a wake-induced vibrations harvester, which consists of a fixed cylinder and a piezoelectric cantilever beam. In this device, the alternating vortices generated by the fluid passing the rigid cylinder induce the vibrations of the piezoelectric beam behind the cylinder and generate electric energy. At the same time, the device can adjust the natural frequency of the oscillator by changing the size and shape of the oscillator. Then Hu et al. proposed a model to calculate the optimal position of the induced vortex, the optimal location of vortex shedding can be determined and the energy harvesting efficiency can be optimized with the model. Although the multi-column structure has the better performance of energy capture, the aerodynamic force on the column is complicated due to the interference between the multiple cylinders. In order to accurately predict the aerodynamic performance of the series of double cylindrical vortex-induced vibrations energy-capturing devices (DSVIVEHS), Zhou et al. [97] used the Boltzmann method to analyze the system. In the experiment, they first used the D2Q9 model to establish a numerical solution model of the vortex-induced vibrations of the cylindrical structure, and then verified the model by the wind tunnel experiments. The numerical solution results are in good agreement with the wind tunnel experiment results. Then they studied the performance of DSVIVEHS. The experimental results show that the energy capture efficiency and working bandwidth of DSVIVEHS can be increased by 6.8 times and 2.67 times, respectively, compared with the single cylinder structure. Subsequently, Wang et al. [98] studied the performance of a series of the square column and cylindrical captive energy device by means of the coupling of electromechanical model and computational fluid dynamics. The coupling calculation process is shown in Fig. 18. Firstly, the external force \( f \) of vortex-induced vibrations piezoelectric energy harvester is obtained by using the lattice Boltzmann method. The system response is obtained by substituting \( f \) into the electromechanical coupling equation, and then the system response is used as the initial condition for the next step. When the error precision meets the specified requirements (the system reaches steady state) the iterative process stops. This method is a good approach for the aerodynamic problems of the complex structures. Song et al. [99] studied the layout optimization of vortex-induced vibrations energy harvester with staggered four-cylinder structures.
Figure 18. The chart of the strong coupling computational process [98].

Table 1

<table>
<thead>
<tr>
<th>Type</th>
<th>Bandwidth</th>
<th>Fluid velocity</th>
<th>Investigator</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIV</td>
<td>1.8-3.2 m/s</td>
<td>3 m/s</td>
<td>Zhang et al. [25]</td>
<td>0.3 mW</td>
</tr>
<tr>
<td></td>
<td>1.76-3.34 m/s</td>
<td>2.8 m/s</td>
<td>Wang et al. [30]</td>
<td>0.0289 mW</td>
</tr>
<tr>
<td></td>
<td>2-3.5 m/s</td>
<td>2.7 m/s</td>
<td>Zhang et al. [38]</td>
<td>0.14 mW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.6 m/s</td>
<td>Zhao et al. [40]</td>
<td>16.55 mW</td>
</tr>
<tr>
<td></td>
<td>0.1-0.3 m/s</td>
<td>0.18 m/s*</td>
<td>Guilherme et al. [44]</td>
<td>80 mW</td>
</tr>
<tr>
<td>Galloping</td>
<td>≥1 m/s</td>
<td>5 m/s</td>
<td>Liu et al. [67]</td>
<td>40 V, 1.6 mW</td>
</tr>
<tr>
<td></td>
<td>≥1.824 m/s</td>
<td>2.646 m/s</td>
<td>Wang et al. [74]</td>
<td>1.6 mW</td>
</tr>
<tr>
<td></td>
<td>≥3 m/s</td>
<td>7 m/s</td>
<td>Noel et al. [77]</td>
<td>14.8 mW</td>
</tr>
<tr>
<td></td>
<td>≥3 m/s</td>
<td>5 m/s (a0=1 m/s²)</td>
<td>Zhao et al. [81]</td>
<td>5.5 mW</td>
</tr>
<tr>
<td>Flutter</td>
<td>≥15 m/s</td>
<td>25 m/s</td>
<td>Grainger et al. [91]</td>
<td>50 mW</td>
</tr>
<tr>
<td></td>
<td>≥3.4 m/s</td>
<td>5.2 m/s</td>
<td>Pasquato et al. [93]</td>
<td>3.5 mW</td>
</tr>
</tbody>
</table>
In recent years, with the further achievements in the flow-induced vibrations research, new energy harvesting based on flow-induced vibrations theory have been developed. Flow-induced vibrations energy harvesting can be adapted to use for wind and hydro energy harvesting according to the properties of the incoming fluid. This section mainly introduces the research progress and application of the two kinds of energy harvesters.

2.1 Wind energy harvester

The traditional blade wind turbines are mainly used to harvest wind energy by the electromagnetic induction principle. They have high requirements for a wind speed, and generally are located in costal, offshore, and other high wind areas. They are suitable for large-scale networking design. The Haliade-X 12MW, the world's powerful offshore wind generator, has a rotor diameter of 220m and a power capacity of 12MW [100]. But its mechanical structure is very complex, and the power generation density is restricted by scale. Therefore, it is generally not suitable for miniaturized design [101]. Besides, wind farms are usually placed far from the consumers, which lead to losses, high maintenance costs, etc. Flow-induced vibrations wind energy harvester converts wind energy into vibration energy by the flow-induced vibrations principle and then converts vibration energy into electric energy through the piezoelectric effect or electromagnetic induction principle. The critical wind speed of the flow-induced vibrations wind energy harvester is affected by the natural frequency and structural parameters of the harvester. The device has low requirements for a wind speed, and its output voltage and power meet the requirements of the sensor. Meanwhile, the structure is always very simple for the flow-induced vibrations energy harvester and their size allows them to be used by distributing them within the populated areas, close to the consumers. There is no any gears, bearings, propellers and other mechanical parts, which significantly reduces their reliability and increases maintenance costs. Therefore, such systems are more suitable for miniaturized design and to use them as the energy source of WSNs system. Moreover, such devices can be distributed inconspicuously over the towns and cities on residential and commercial buildings, organizing an alternative network.

Vortex Bladeless, which is a new wind power generation equipment, is invented by a Spanish company [7]. This harvester is designed to improve the efficiency of wind energy harvesting and to solve the transportation, installation, and maintenance problems of traditional wind turbines [102]. The structure of Vortex Bladeless is...
shown in Fig. 19. This device utilizes the principle of vortex-induced vibrations to make the cylinder vibrate transversely, and then convert the vibrations of the cylinder into electric energy through the electromagnetic generator at the bottom. The cylinder in the harvester adopts a new material such as carbon fiber to reduce the weight and the natural frequency of the equipment, so that the starting wind speed of the cylinder can be reduced to 3 m/s. Meanwhile, the device adjusts the stiffness of the system according to the wind speed by means of a magnetic confinement to coordinate the natural frequency of the system and the frequency of vortex shedding, and widen the working bandwidth. The schematic diagram of the magnetic confinement is shown in Fig. 20 [103]. In order to study the influence of the column structure on the bladeless wind turbine (BWT), Chizfahm et al. [104] used four different cylinders to study the BWT performance, as shown in Fig. 21. Among them, BWT1 and BWT2 adopt a flexible equilateral section cylinder and flexible variable section cylinder respectively. BWT3 adopts the combination of a flexible beam and rigid equal section cylinder, and BWT4 adopts the combination of a flexible beam and rigid variable section. The experiments show that BWT2 and BWT4 have better performance when the wind speed is high (the vortex shedding frequency is higher than the natural frequency of the structure), BWT1 and BWT3 have better performance when the wind speed is low (the vortex shedding frequency is lower than the natural frequency of the structure). In addition, compared with flexible column structure, the combination of flexible beam and rigid column structure has better performance. Then, Yazdi et al. [105] found that the vortex shedding frequency of BWT does not match the natural frequency of the system under a high wind speed. They proposed a quadratic gain-scheduling controller to improve the natural frequency of the structure and match the vortex shedding frequency at high wind speeds. The output power of BWT with the dispatching controller is up to 1kW. In addition to the above harvesters, Wang et al. [106] studied a new type of the energy harvester based on vein structure transformation, and its structure is shown in Fig. 22. The harvester uses triangular leaves based on the venation structure of the leaves of dicotyledonous plants as energy capture elements, and it uses the principle of VIVs to harvest wind energy. The research shows that the efficiency of the energy harvester is greatly affected by the venation structure, and the efficiency of the device with venation is 4-6 times higher than that of the device without venation. Zhang et al. [107] constructed a curved beam type vortex-excited vibrations enhanced energy harvester as shown in Fig. 23, which makes the pressure on the curved beam approach the buckling strength by introducing a spring to adjust the load on the bending beam. The experimental results suggest that the output voltage and power of the device are significantly higher than that of the traditional cantilever energy capture device, when the wind speed is close to 10m/s, the effective output voltage can be increased by nearly 5 times. In addition, Gkoumas, Wang et al. [108-110] proposed that the energy in the airflow of heating, ventilation and air conditioning (HVAC) can be collected through the principle of flow-induced vibrations, so as to optimize building energy consumption and realize the purpose of building energy conservation. The MEMS energy harvester proposed by He et al. [111] provides energy for the sensor by applying piezoelectric materials to the MEMS
system, which is of great significance for the miniaturization design of the wind energy harvester.

Figure 19. Evolution of the mast diameter according to height [103].

Figure 20. Schematic diagram of Oscillator with a magnetic tuning system diagram [103].

Figure 21. The bladeless wind turbines; (a)BWT1 (b)BWT2 (c)BWT3 (d)BWT4 [104].
The common flutter type wind energy harvesters can be divided into piezoelectric structure, electromagnetic structure, and electrostatic structure according to different working mechanisms. The structure of the airfoil piezoelectric flutter energy harvester is generally composed of a wing type oscillator, a hinge link structure, a flexible beam, and a trapping circuit. When fluid passes the airfoil oscillator, it drives the bending and vibrations of the piezoelectric beam while rotating, and convert fluid energy to electric energy [112]. In order to improve the efficiency and stability of the harvester, Orrego et al. [113] proposed a flutter energy harvester named "inverted flag", which consists of a set of flexible piezoelectric film, a rigid-type rotating shaft and self-aligning mechanism. A relatively simple structure is shown in Fig. 24. The experimental results show that the device can output 1-5mW/cm³ at the wind speed of 5-9m/s, and maintain a continuous output of 0.1-0.4mW/cm³ even at low wind speeds (2.5-4.5m/s), and be less affected by wind speed fluctuations. At the same time, the "inverted flag" is dynamically adjusted by the self-aligning mechanism, the temperature sensor data output is increased by nearly 20 times, the average daytime temperature sensor outputs 1.5 times more data per minute, and provides the data output every ten minutes at night, which basically is associated with the normal operation of the temperature sensor. The electromagnetic flutter energy harvester mainly collects wind energy through the principle of the electromagnetic induction. In order to make full use of the mechanical energy generated by the fluttering pitching motion and the vertical lifting motion, Liu et al. [114] proposed a nonlinear
electromagnetic energy trapping device as shown in Fig. 25, which can realize MDOF cutting a magnetic sense line movement to improve the efficiency of energy harvesting. Boccalero et al. [115] proposed a new coupled flutter energy harvester, which is shown in Fig. 26. The device replaces the elastic material in the conventional electromagnetic flutter energy capture device with a dielectric elastomer. It implements the synergistic power generation of the electromagnetic and dielectric elastomer by stretching and reducing the dielectric elastomer based on the vertical lifting motion of the flutter, and then improves the efficiency of captive energy. Aquino et al. studied the use of electromagnetic flutter energy capture devices in buildings. With the development of intelligent smart cities, low-power small appliances and milliwatt-class wireless sensors, data recorders and other small power-consuming electronics will be extensively used. Therefore, it is a good choice to use a flutter-type energy harvester to achieve an independent power supply [116, 117]. The electrostatic energy harvester is usually designed based on the principle of the triboelectric charging. The flexible mold rubs against the fixed rail under the action of the fluid to realize the transfer of an electric charge and convert the fluid energy into electric energy. Perez et al. [118] tested the performance of an electrostatic film with a size of 5 cm × 2 cm × 50 μm at a wind speed of 15 m/s. In the experiment, Perez et al. [118] installed four sets of 1 cm × 2 cm electrodes on the sidewall behind the film to collects the charge. The results show that the device's energy output can reach 180μW. Phan et al. [119] proposed a nano-friction generator, which can harvest wind energy based on the flutter principle, as shown in Fig. 27. The device is mainly composed of a flutter film and rubber belt. When air passes through it, the flutter film will vibrate and then generate electric energy by friction with the rubber belt. Under normal operating conditions, the output power of the single-layer flutter nanogenerator reaches 0.33μW. The output power can be increased through multi-layer stacking to meet the energy demand of a small sensor.

Figure 24. Inverted flag [113].
plunge and pitch motions of the coil immersed in the magnetic field [114].

Figure 26. Picture of FLEHAP device exploiting EMc(a), and a sketch of system using both EMc and DEGs(b) [115].

Figure 27. Aerodynamic and aeroelastic flutter-driven triboelectric nanogenerators [119].

2.2 Hydro energy harvester

In recent years, with the increasingly serious environmental problems in the oceans, rivers, and lakes, environmental ecology has gradually become an important factor restricting the development of hydro energy harvesting technology. In addition, the complex and changeable water environment has also brought great difficulties to the deployment of energy harvesters. Many domestic and foreign researchers have recently conducted in-depth research on water energy harvesting [120-128]. The structure of the fluid-induced vibrations water energy harvester is simple and can adapt to the harsh and complex environment, which is suitable for underwater work. In addition, the fluid-induced vibrations energy harvesters has little impact on the environment and ecology, and they will not cause much impact on the surrounding environment [129].

At present, the most common energy harvesters include horizontal and vertical axis turbines, oscillating hydrofoil power generation devices, venturi differential pressure turbines, Archimedes screw turbines, tidal kite turbines, water storage energy harvesting, VIVACE harvester, etc.[130] The VIVACE harvester was proposed by Bernitsas and Raghavan et al. [6] at the University of Michigan, and its structure is shown in Fig. 28. The harvester is mainly composed of a vibrating cylinder, a
transmission structure, a generator and other parts. Under the action of a water flow
the cylinder in vortex-induced vibrations converts the fluid energy into vibrational
energy, which is then transmitted energy through, then the transmission structure can
transform a linear motion into the rotary motion of the rotor in the generator, finally
the fluid energy is converted into electrical energy. The experimental results show that
the harvester has a wide operating range, and it can still operate normally and
maintain a high capture energy efficiency even at the flow speed as low as 0.25m/s,
thereby validating the water flow energy harvesting. The success of VIVACE is of
great significance, and it has greatly promoted the development of the research on
water energy harvesting. The bionic structure like an airfoil harvests energy by
simulating the swing of the tail of the animal, and it has a better research prospect due
to its great hydrodynamic properties [131]. BioSTREAM [132] is a marine tidal
energy harvesting facility developed by BPS company in Australia, and the model is
shown in Fig. 29. The harvester is mainly composed of a fixed base, a tail structure, a
hydraulic cylinder, O-Drive (DC power generation device) and other parts. The attack
angle of the tail fin and the direction of the incoming flow are kept consistent by
active control. Under the action of the fluid lift force, the tail fin structure rotates
around the fixed base to compress the fluid in the tail hydraulic cylinder. Finally, the
O-Drive uses high-pressure fluid to generate DC power, which realizes the conversion
of fluid energy to electric energy. Barbarelli et al. [133] proposed a new offshore
energy harvester, which is shown in Fig. 30. It is mainly composed of an airfoil blade,
a four-link connection structure, a piston pump, a reservoir, a hydraulic generator set
and other parts. The device turns the tidal horizontal flow into the up-down movement
of the blades, and drives the pistons to reciprocate through the four-bar structure, then
pushes the generator set to work by the pressure difference, the conversion of tidal
energy into electricity can be finally realized. The harvester arranges vulnerable parts
including generator sets on the shore, and the blade oscillators are immersed in the
offshore sea level, so that it reduces the cost of installation and maintenance. However,
it will reduce the efficiency of the energy capture due to friction and wear of the
connecting mechanism at the same time. Subsequently, Barbarelli et al. [134] assessed
the performance of the energy harvester, the preliminary evaluation suggests that
when the tidal flow velocity reaches 3m/s, its output power will exceed 120kW and
the energy conversion efficiency will reach 23% for a device with a blade length of
8m and an upper and lower migration range of 5m.
Figure 28. The structures of VIVACE [6].

Figure 29. BioSTREAM [132].

Figure 30. System configuration and blade particular [133].

**Table 2**

Summary of flow induced vibration energy harvester mentioned above

<table>
<thead>
<tr>
<th>Type</th>
<th>Bandwith</th>
<th>Fluid velocity</th>
<th>Investigator</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind energy harvester</td>
<td>3m/s-12m/s</td>
<td>Nominal speed</td>
<td>Vortex Bladeless [103]</td>
<td>100W</td>
</tr>
<tr>
<td></td>
<td>≥1m/s</td>
<td>20m/s</td>
<td>Yazdi et al. [107]</td>
<td>10000W</td>
</tr>
<tr>
<td></td>
<td>≥6m/s</td>
<td>10m/s</td>
<td>Wang et al. [108]</td>
<td>0.457μW/cm²</td>
</tr>
<tr>
<td></td>
<td>≥4m/s</td>
<td>14m/s</td>
<td>Zhang et al. [109]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>≥3.6m/s</td>
<td>7m/s</td>
<td>Wang et al. [112]</td>
<td>275mW</td>
</tr>
<tr>
<td></td>
<td>≥4m/s</td>
<td>7.3m/s</td>
<td>He et al. [113]</td>
<td>0.14μW</td>
</tr>
<tr>
<td></td>
<td>≥4.2m/s</td>
<td>9m/s</td>
<td>Inverte flag [114]</td>
<td>5mW/cm²</td>
</tr>
<tr>
<td></td>
<td>≥8.2m/s</td>
<td>13m/s</td>
<td>Liu et al. [115]</td>
<td>40mW</td>
</tr>
<tr>
<td></td>
<td>≥2.5m/s</td>
<td>6m/s</td>
<td>Boccalero et al. [116]</td>
<td>22mW</td>
</tr>
</tbody>
</table>
### 3 Prospects and Challenges

Based on the different mechanisms of flow-induced vibrations, this paper summarizes the research progress of flow-induced vibrations energy harvesting of four types: vortex-induced vibrations, galloping, flutter, and buffeting. According to the different sources of fluid energy, the common wind and water energy harvesters are discussed.

The energy harvesting by flow-induced vibrations has a great application perspective and can solve the problem of powering wireless sensors networks. With the rapid development of WSNs and Internet of Things technology, the flow-induced vibrations energy harvesters will be proliferating into these and other sectors where alternative, independent and distributed energy sources are required. Of course, one must also recognize the urgent problems that the flow-induced vibrations energy harvesting technology faces right now [9]. For example, the vibration frequency of Vaneless generators is lower than that of others, which may cause serious infrasound crisis once it is adapted widely. Due to the size and material limitation of piezoelectric energy harvesters, the power generation is limited, which makes it difficult to meet the actual requirements of sensors. These devices still need research and optimization to work effectively and sustainably in spite of geographical environment, weather and others factors. Although the water energy harvester has a little impact on the ecosystem, it also has some problems, for instance a low energy conversion rate. At present, most of the flow-induced vibrations energy harvesters are still at their experimental stage, and there is still a long way ahead before their deployment and wider proliferation is achieved. Meanwhile, the flow-induced vibrations energy harvesting technology can be combined with the current mature photovoltaic power generation technology, the fan power generation technology, and the excitation vibration energy harvesting technology to ensure the normal operation of the flow-induced vibrations energy-trapping devices under multiple working conditions.

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